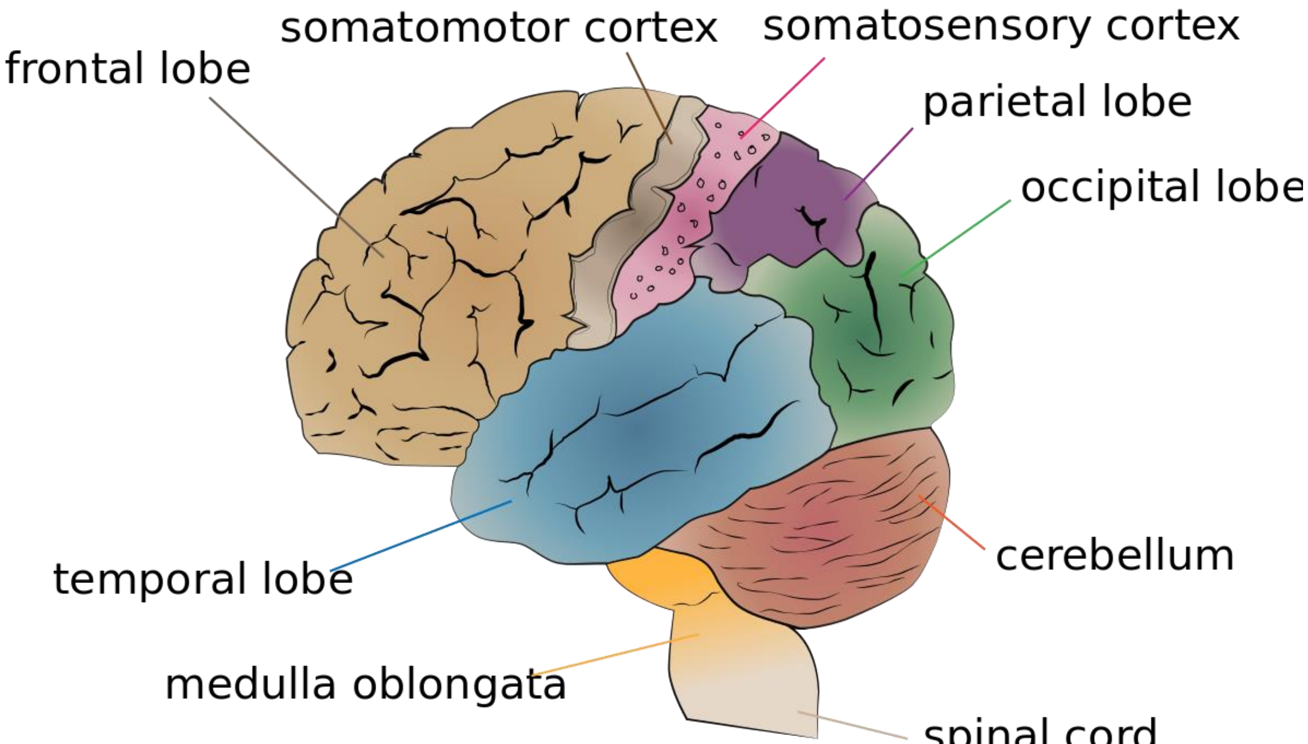
BCI-S2022

Basics of Neuroscience for BCI

The Human Brain



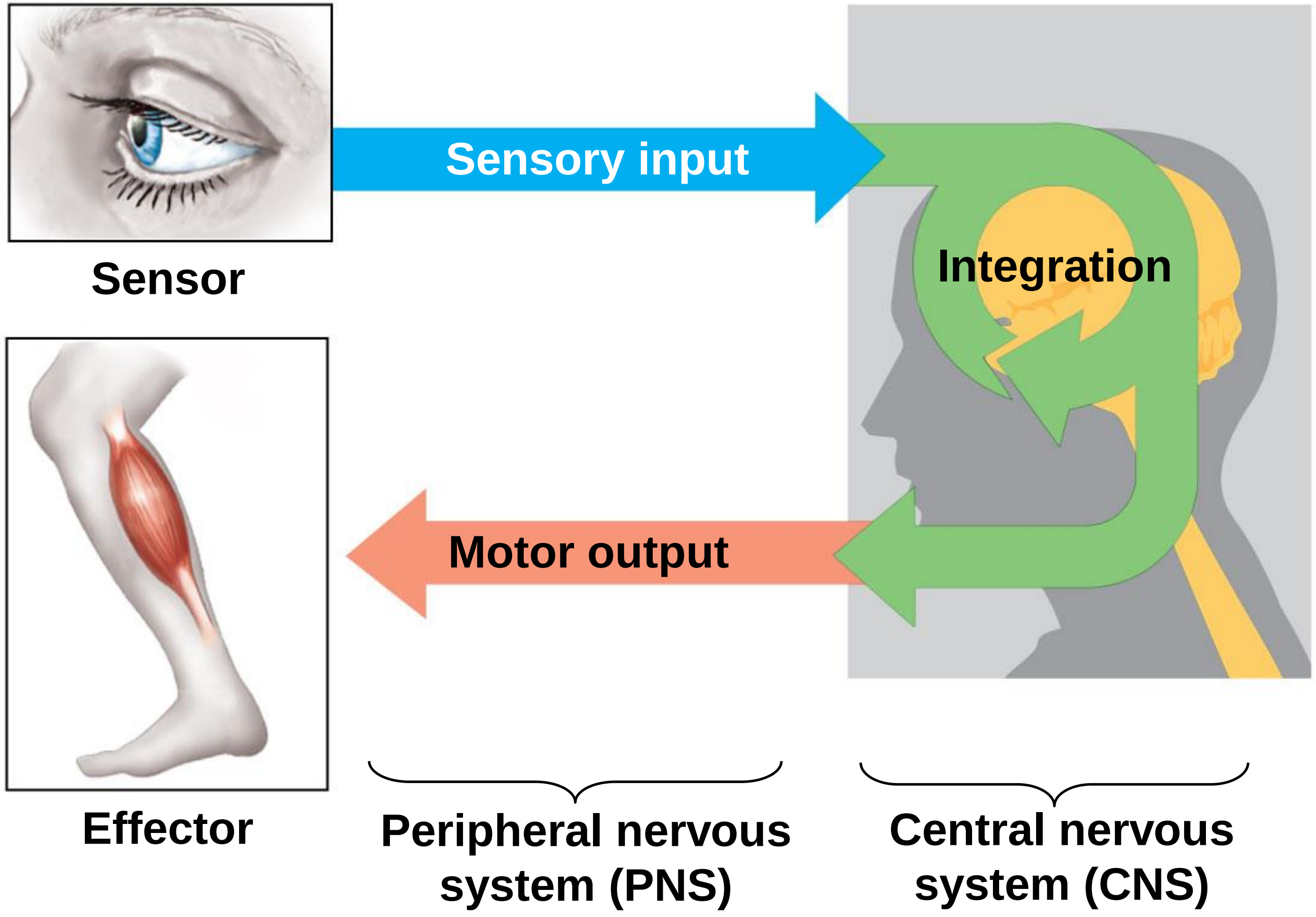
The Neuron

- The brain's unique information processing capabilities arise from its massively parallel and distributed way of computing.
- The workhorse of the brain is a type of cell known as a ***NEURON***.
- Neuron is a complex electrochemical device that receives information from hundreds of other neurons, processes this information, and conveys its output to hundreds of other neurons

The Neuron

- The neuron can be regarded as a leaky bag of charged liquid.
- The membrane of a neuron is made up of a lipid bi-layer that is impermeable except for openings called ionic channel.
- The ionic channels selectively allow the passage of a few ions

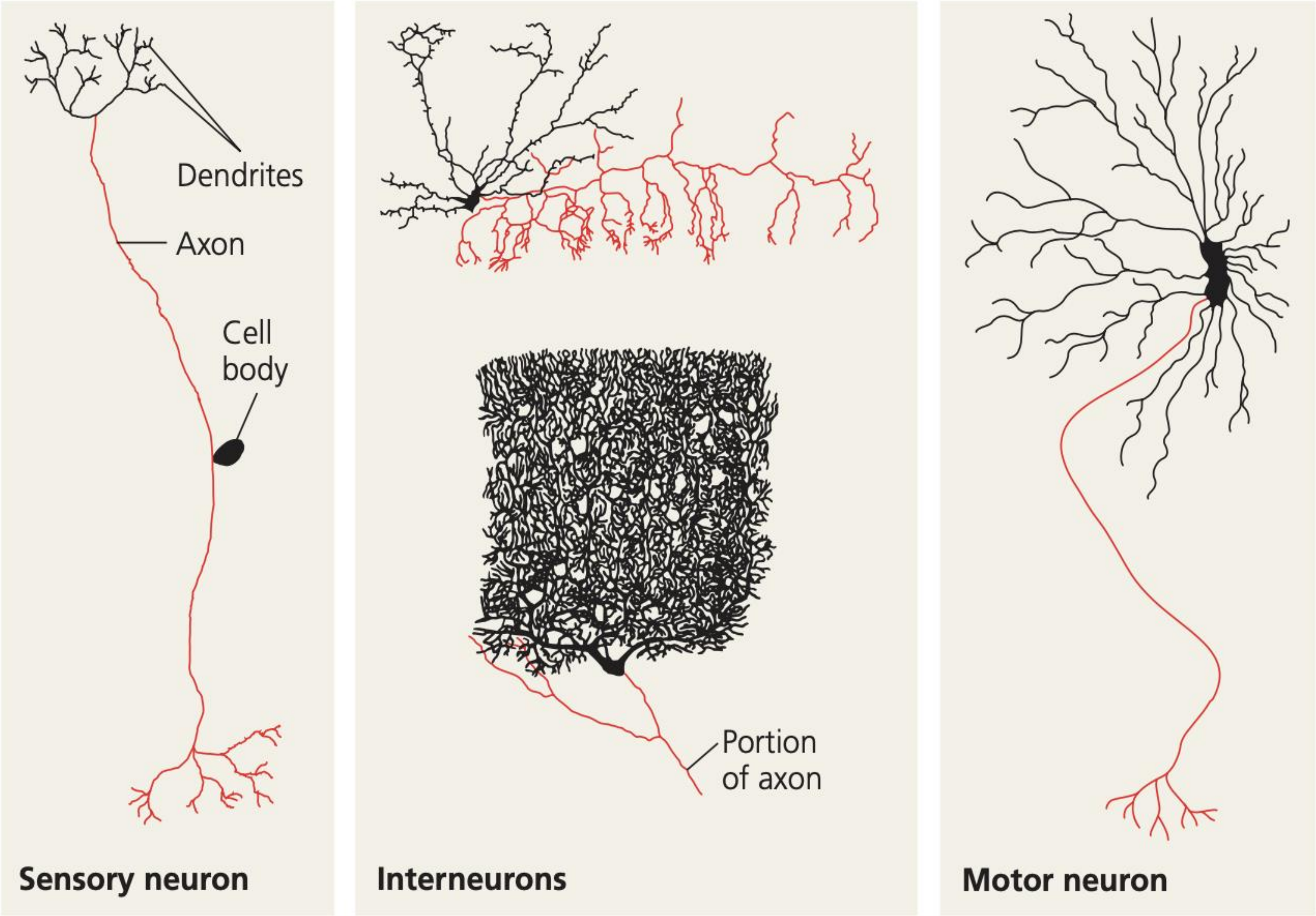
REVISIT : Introduction to Information Processing



© 2011 Pearson Education, Inc.

Many animals have a complex nervous system that consists of

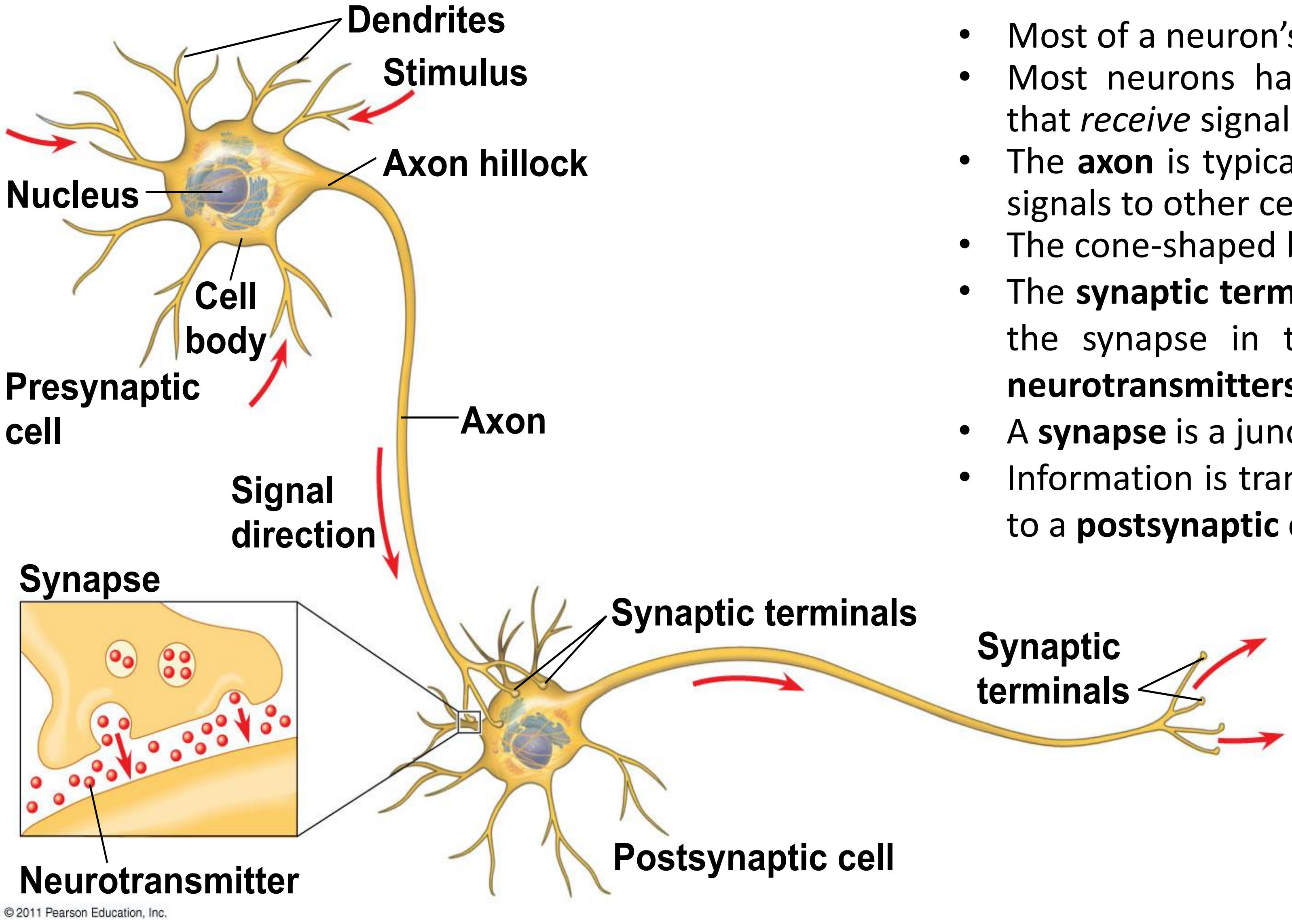
- A **central nervous system (CNS)** where integration takes place; this includes the brain and a nerve cord
- A **peripheral nervous system (PNS)**, which carries information into and out of the CNS
- The neurons of the PNS, when bundled together, form **nerves**



Structural diversity of neurons. *Cell bodies and dendrites are black in these diagrams; axons are red. In the sensory neuron, unlike the other neurons here, the cell body is located partway along the axon that conveys signals from the dendrites to the axon's terminal branches.*

- Sensors detect external stimuli and internal conditions and transmit information along **sensory neurons**
- Sensory information is sent to the brain, where **interneurons** integrate the information
- Motor output leaves the brain via **motor neurons**, which trigger muscle or gland activity

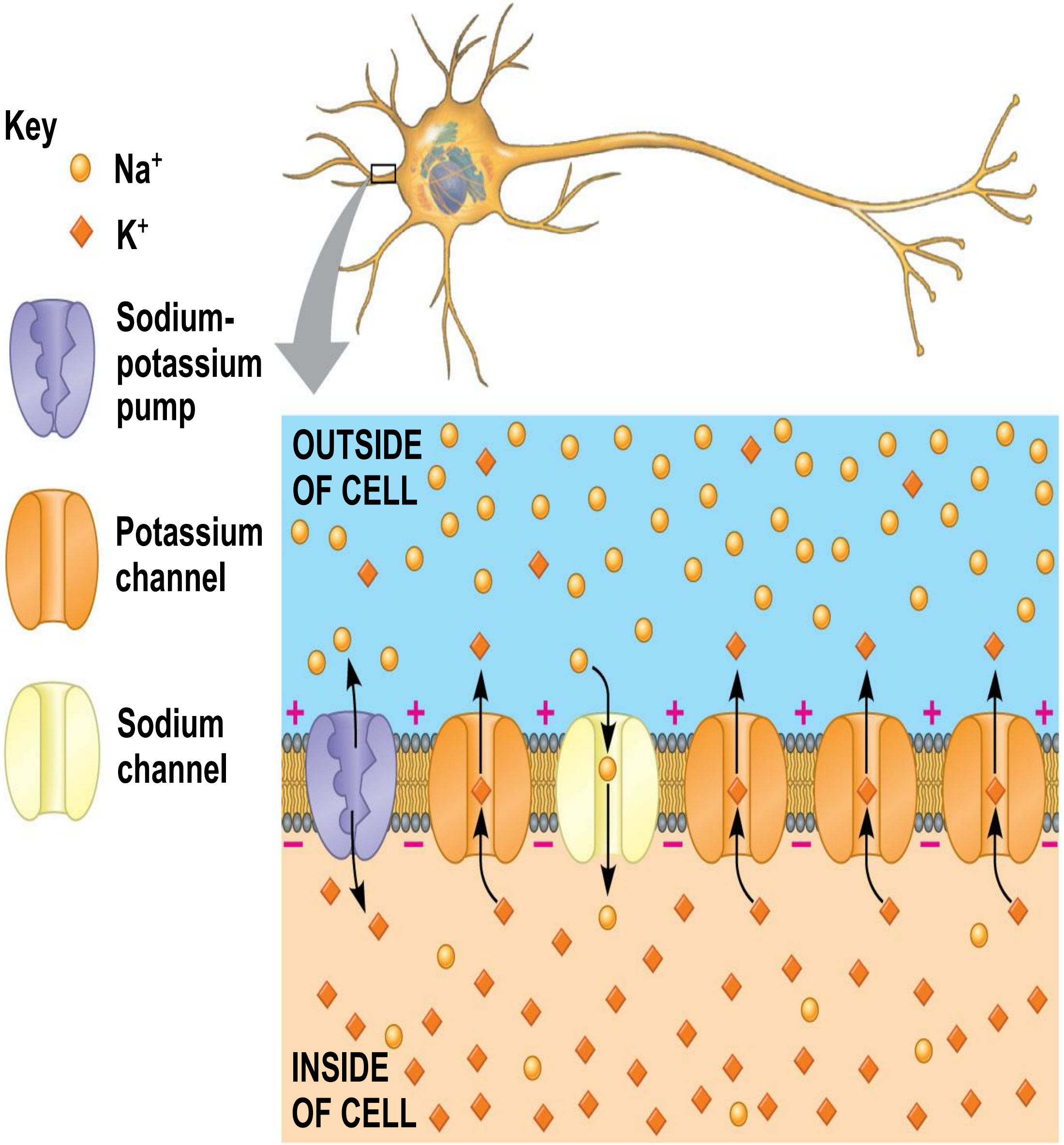
Neuron Structure and Function



- Most of a neuron's organelles are in the **cell body.**
- Most neurons have **dendrites**, highly branched extensions that *receive* signals from other neurons.
- The **axon** is typically a much longer extension that transmits signals to other cells at synapses.
- The cone-shaped base of an axon is called the **axon hillock.**
- The **synaptic terminal** of one axon passes information across the synapse in the form of chemical messengers called **neurotransmitters.**
- A **synapse** is a junction between an axon and another cell
- Information is transmitted from a **presynaptic cell** (a neuron) to a **postsynaptic cell** (a neuron, muscle, or gland cell).

Ion pumps and ion channels establish the resting potential of a neuron

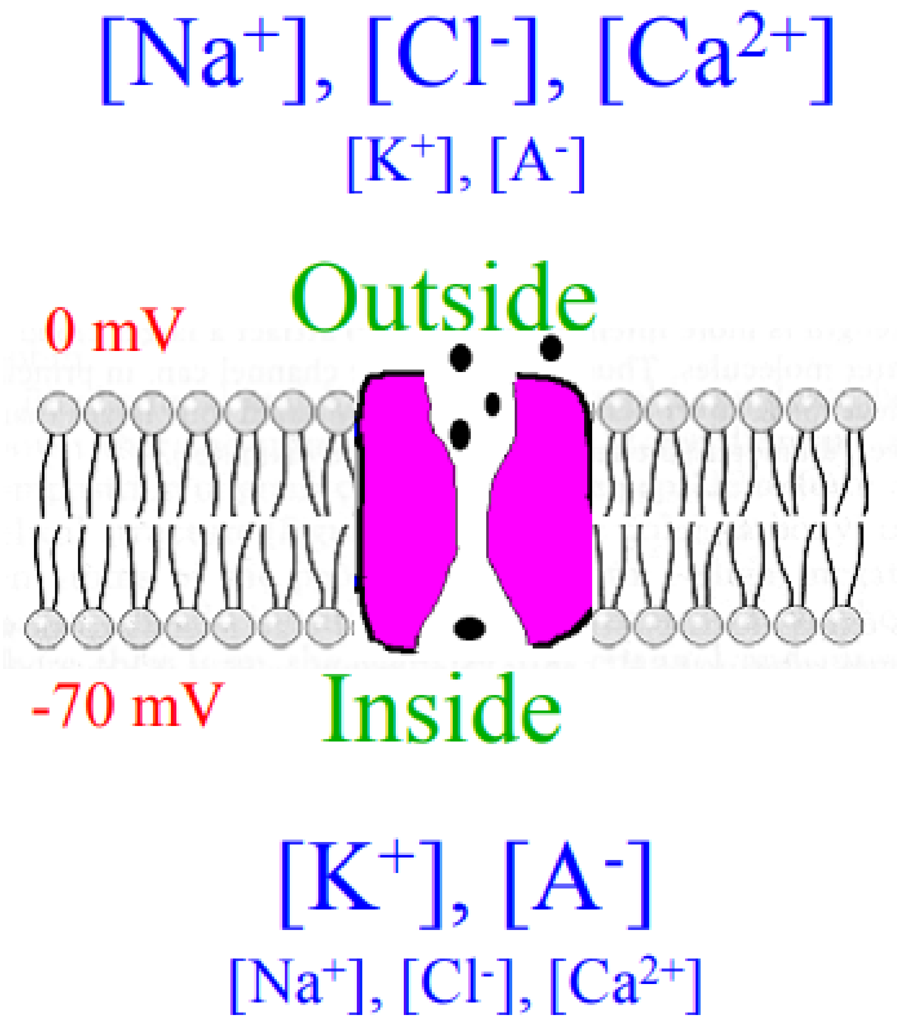
- Every cell has a voltage (difference in electrical charge) across its plasma membrane called a **membrane potential.**
- The **resting potential** is the membrane potential of a neuron not sending signals.
- Changes in membrane potential act as signals, transmitting and processing information.
- In a mammalian neuron at resting potential, the concentration of K^+ is highest inside the cell, while the concentration of Na^+ is highest outside the cell.
- The opening of **ion channels** in the plasma membrane converts chemical potential to electrical potential.
- A neuron at resting potential contains many open K^+ channels and fewer open Na^+ channels; K^+ diffuses out of the cell.
- The resulting buildup of negative charge within the neuron is the major source of membrane potential.



© 2011 Pearson Education, Inc.

The Electrical Personality of a Neuron

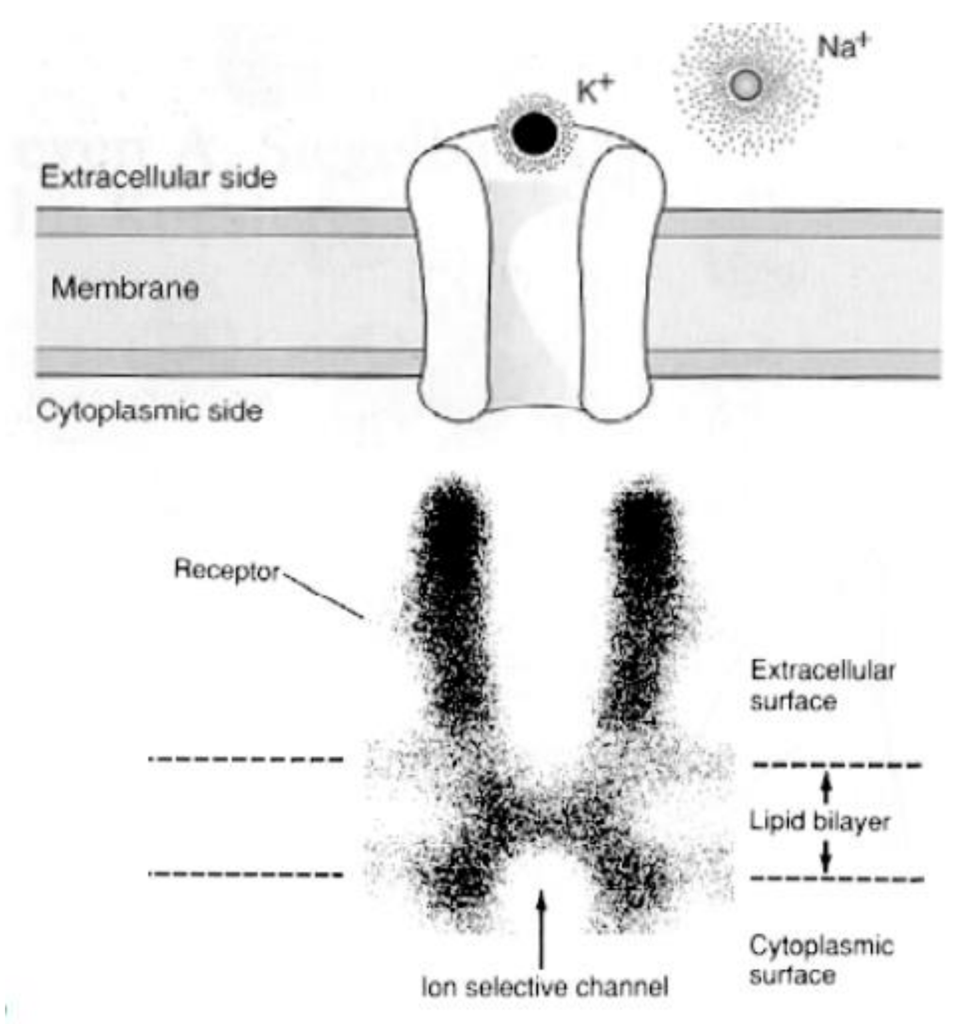
- Each neuron maintains a potential difference across its membrane
- Inside is ±70 to ±80 mV relative to outside
- [Na+], [Cl-] and [Ca2+] higher outside; [K+] and organic anions [A-] higher inside
- Ionic pump maintains -70 mV difference by expelling Na+ out and allowing K+ ions in



How can the electrical potential be changed in local regions of a neuron?

Ionic Channels: The Gatekeepers

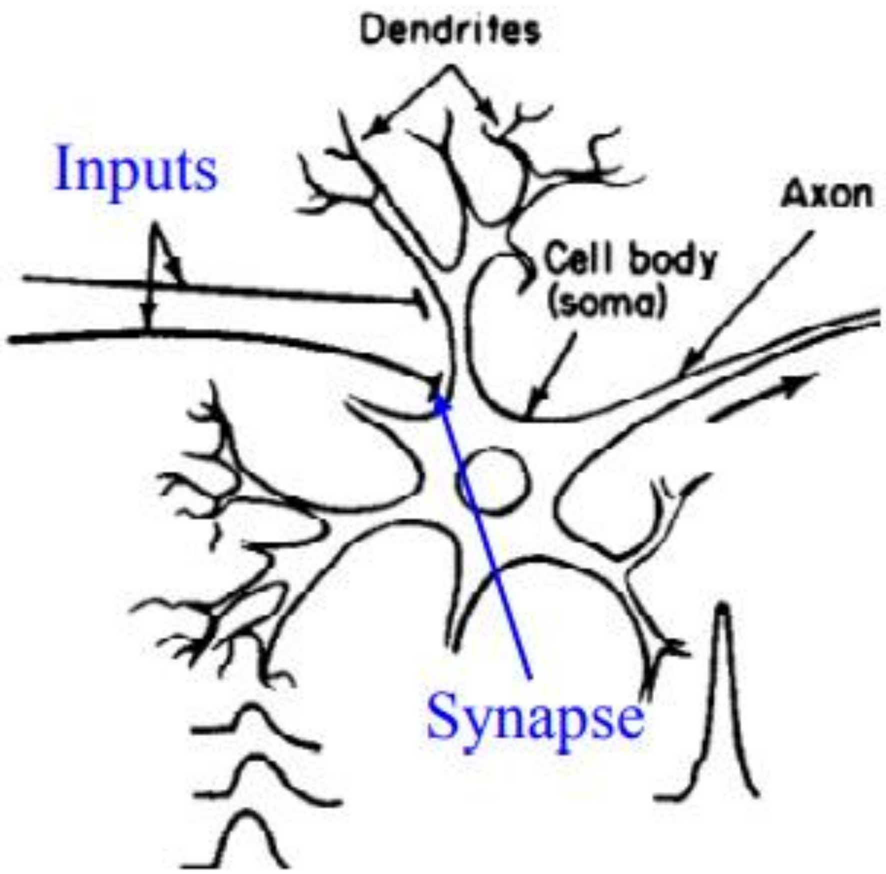
- Proteins in membranes act as channels that allow specific ions to pass through.
  - E.g.: Pass K+ but not Cl- or Na+
- These **IONIC CHANNELS** are gated
  - Voltage-gated: Probability of opening depends on membrane voltage
  - Chemically-gated: Binding to a chemical causes channel to open
  - Mechanically-gated: Sensitive to pressure or stretch



From Kandel, Schwartz, Jessel, Principles of Neural Science, 3rd edn., 1991, pgs. 68 & 137

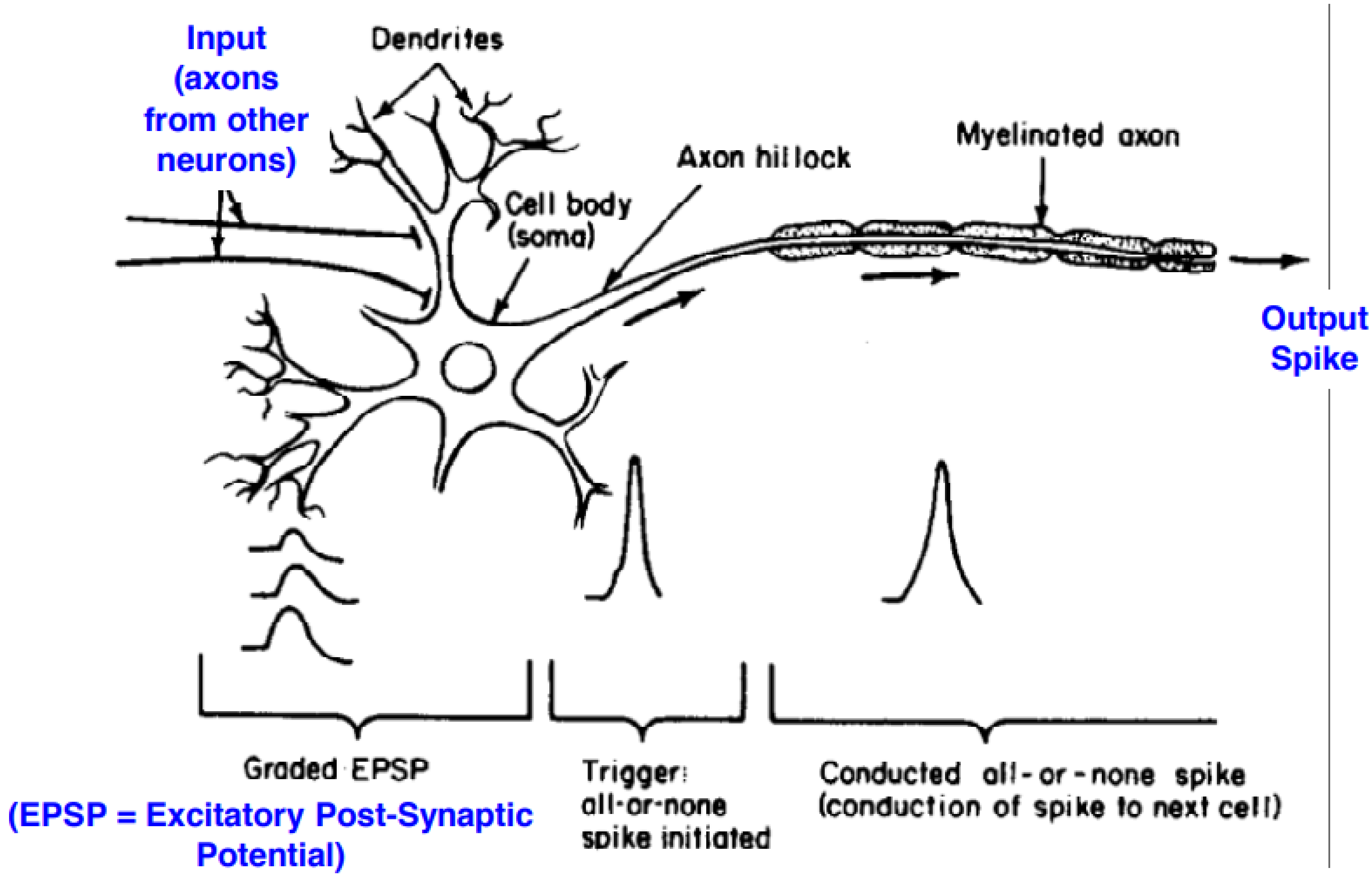
Gated Channels allow Neuronal Signaling

- Inputs from other neurons -> chemically-gated channels (at “synapses”) -> Changes in local membrane potential
- This causes opening/closing of voltage-gated channels in dendrites, body, and axon, resulting in depolarization (positive change in voltage) or hyperpolarization (negative change)



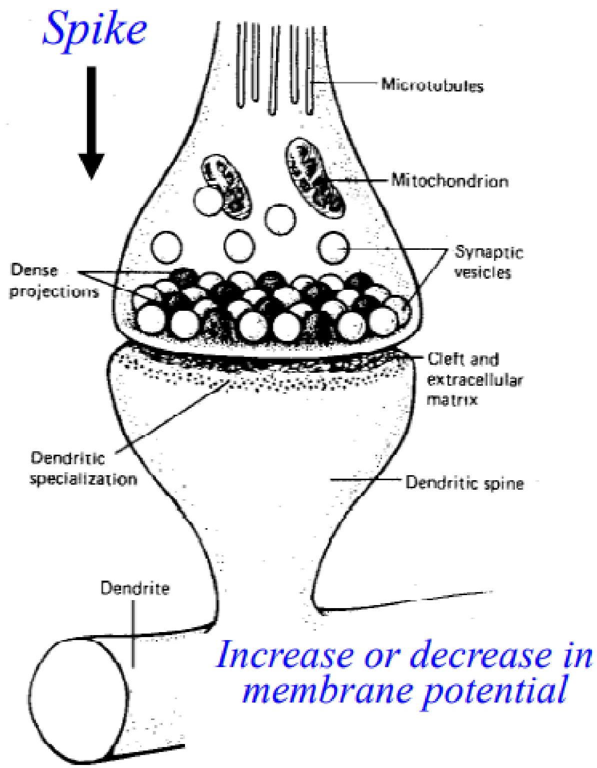
Regions of Neurons

- Neurons in different regions of the brain have different morphological structures
- The typical structure includes a cell body (called the soma) connected to a tree-like structure with branches called dendrites
- A single branch called the axon that emanates from the soma and conveys the output spike to other neurons.
- The spike is typically initiated near the junction of the soma and axon and propagates down the length of the axon.
- Many axons are covered by myelin, a white sheath that significantly boosts the speed of propagation of the spike over long distances.


Input
(axons
from other
neurons)
Dendrites
Cell body
(soma)
Axon hillock
Myelinated axon
Output
Spike
Graded EPSP
(EPSP = Excitatory Post-Synaptic
Potential)
Trigger:
all-or-none
spike initiated
Conducted all-or-none spike
(conduction of spike to next cell)

Synapse

- Neurons communicate with each other through connections known as synapses.
- Synapses can be electrical but are more typically chemical.
- A synapse is essentially a gap or cleft between the axon of one neuron (called the presynaptic neuron) and a dendrite (or soma) of another neuron (called the postsynaptic neuron)



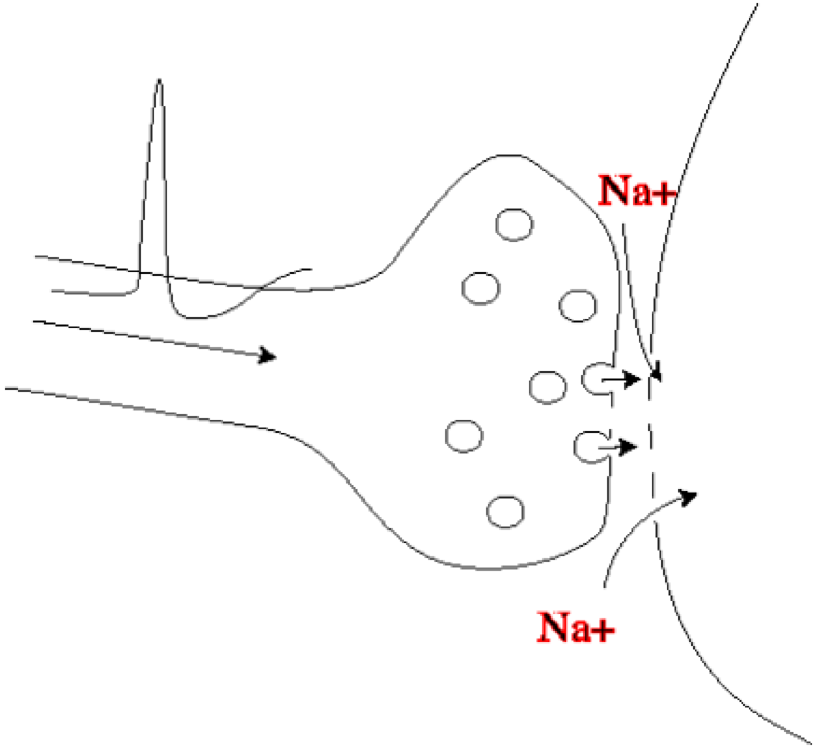
Synapse

- When an action potential arrives from a presynaptic neuron, it causes the release of chemicals known as neurotransmitters into the synaptic cleft.
- These chemicals in turn bind to the ionic channels (or receptors) on the postsynaptic neuron, causing these *channels to open*, thereby influencing the local membrane potential of the postsynaptic cell.

Synapse

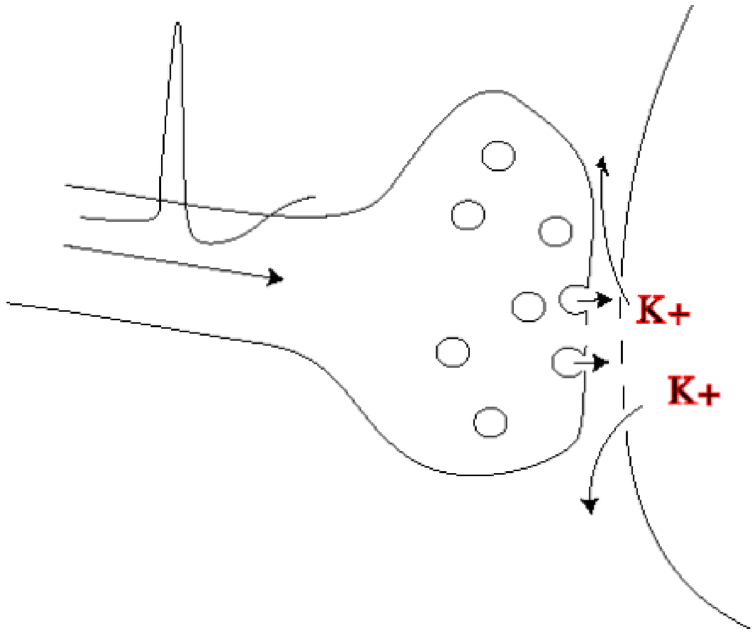
- Synapses can be excitatory or inhibitory.
- Excitatory synapses cause a momentary increase in the local membrane potential of the postsynaptic cell.
  - This increase is called an excitatory postsynaptic potential (EPSP).
  - EPSPs contribute to a higher probability of firing a spike by the postsynaptic cell.
- Inhibitory synapses do the opposite, temporarily decrease the local membrane potential of the postsynaptic cell
  - They cause inhibitory postsynaptic potentials (IPSPs)
- A neuron is called excitatory or inhibitory based on the kind of synapse it forms with *postsynaptic neurons*

An Excitatory Synapse



Input spike → Neurotransmitter release → Binds to Na channels (which open) → Na+ influx → Depolarization due to EPSP (excitatory postsynaptic potential)

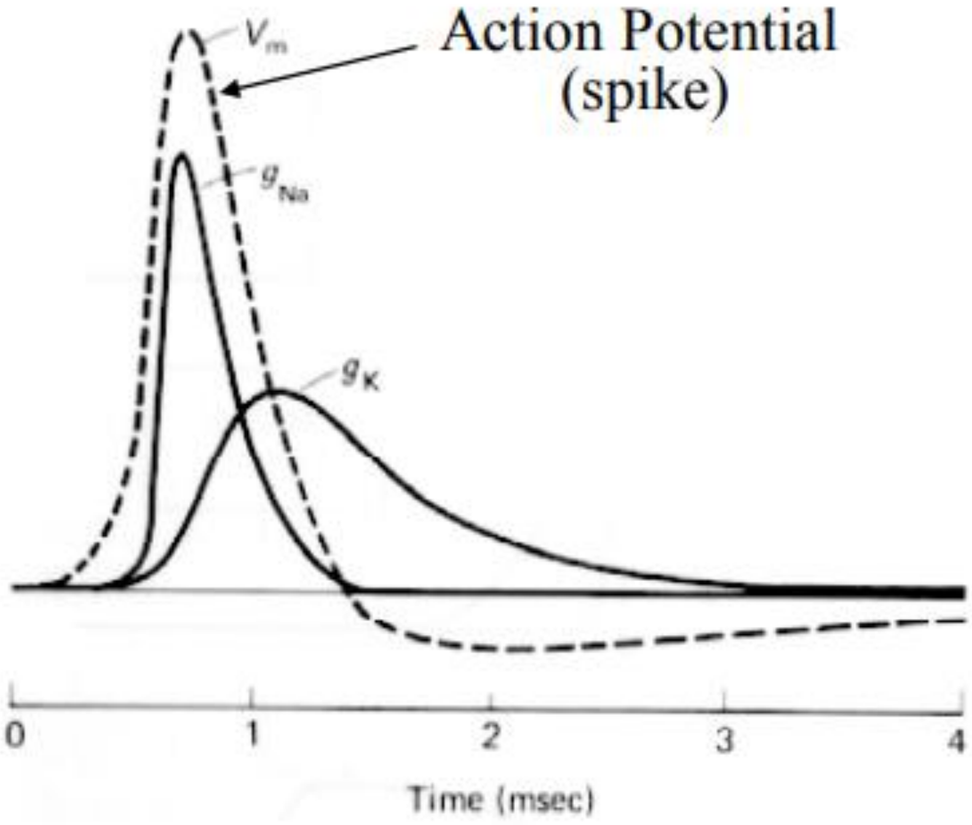
An Inhibitory Synapse



Input spike → Neurotransmitter release → Binds to K channels → K+ leaves cell → Hyperpolarization due to IPSP (inhibitory postsynaptic potential)

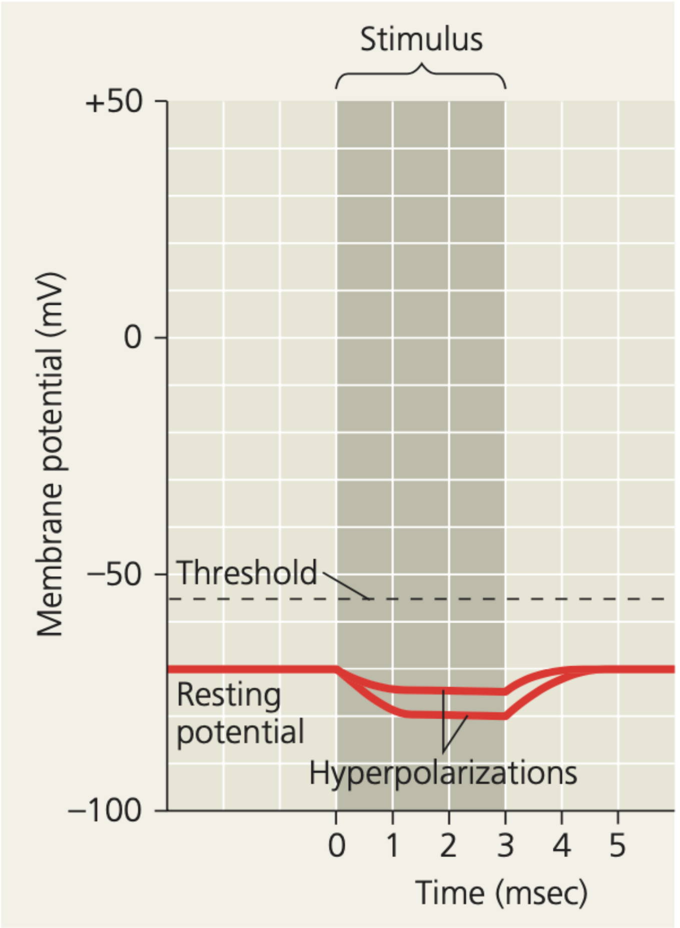
Action Potential or Spikes

- When the neuron receives sufficiently strong inputs from other neurons a cascade of events is triggered
- Rapid influx of Na+ ions into the cell
  - *Causing the membrane potential to rise rapidly.*
- The opening of K+ channels triggers the outflux of K+ ions
  - *Causing a drop in the membrane potential.*
- This rapid rise and fall of the membrane potential is called an ***action potential*** or **spike** and represents the dominant mode of communication between one neuron and another.

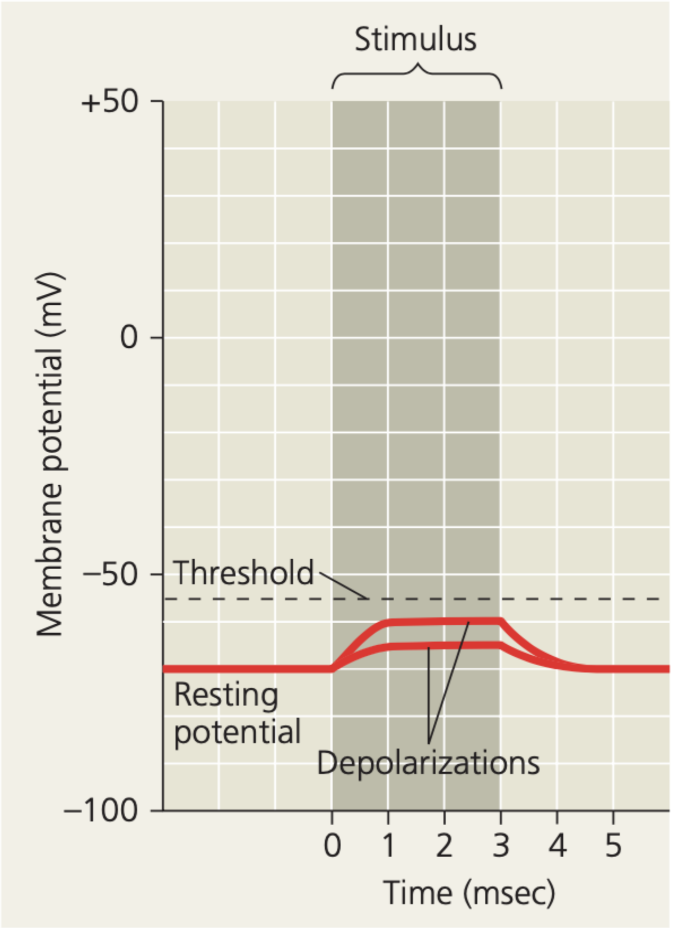


From Kandel, Schwartz, Jessel, Principles of Neural Science, 3rd edn., 1991, pg. 110

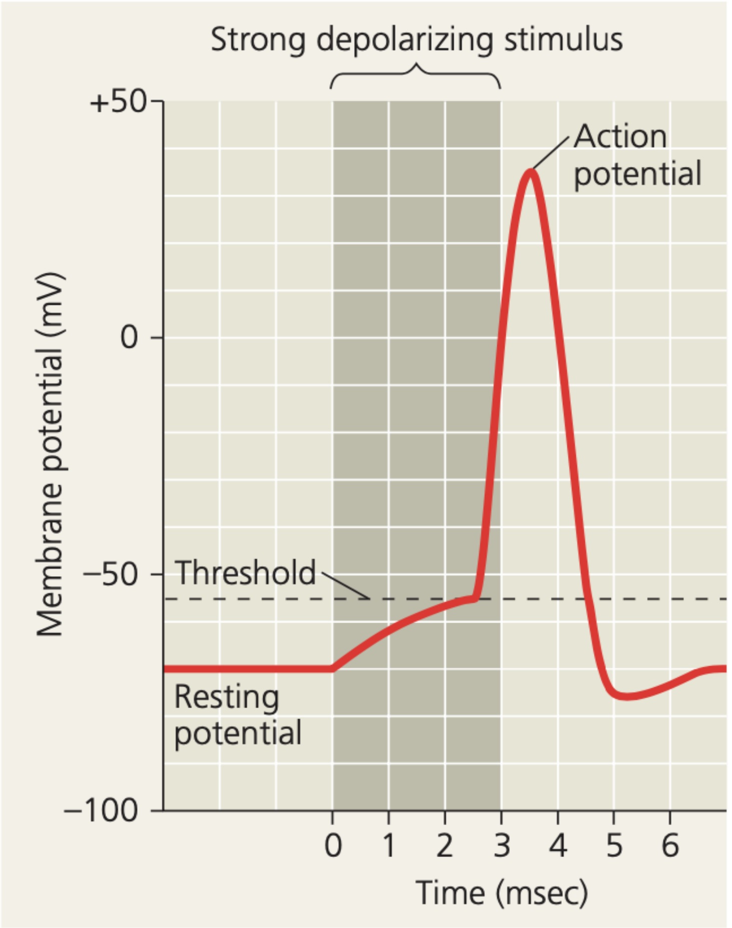
Graded potentials and an action potential in a neuron.



(a) Graded hyperpolarizations produced by two stimuli that increase membrane permeability to K^+. The larger stimulus produces a larger hyperpolarization.



(b) Graded depolarizations produced by two stimuli that increase membrane permeability to Na^+. The larger stimulus produces a larger depolarization.



(c) Action potential triggered by a depolarization that reaches the threshold.

Spike Generation

- The generation of a spike by a neuron involves a complex cascade of events involving sodium and potassium channels
- This process can be simplified into a simple threshold model of spike generation.
  - *When the neuron receives sufficiently strong inputs from its synapses for its membrane potential to cross a neuron-specific threshold, a spike is emitted.*

Synaptic plasticity: Adapting the connections

- **Long Term Potentiation (LTP):** Increase in synaptic strength of a synaptic connection between two neurons caused by correlated firing of the two neurons
  - lasts for several hours or more.
- Measured as an increase in the excitatory postsynaptic potential (EPSP) caused by presynaptic spikes
- LTP has been found in several brain areas including the hippocampus and the neocortex.
- Note: *LTP is regarded as a biological implementation of Donald Hebb's famous postulate (also called Hebbian learning or Hebbian plasticity) that if a neuron A is consistently involved in causing another neuron B to fire, then the strength of the connection from A to B should be increased.*

Synaptic plasticity: Adapting the connections

- **Long-term depression or LTD:** Decrease in the strength of a synaptic connection caused
  - by uncorrelated firing between the two neurons involved.
  - Reduction in synaptic strength that lasts for several hours or more
- LTD has been observed most prominently in the cerebellum, although it also coexists with LTP in the hippocampus, neocortex, and other brain areas

Synaptic plasticity: Adapting the connections

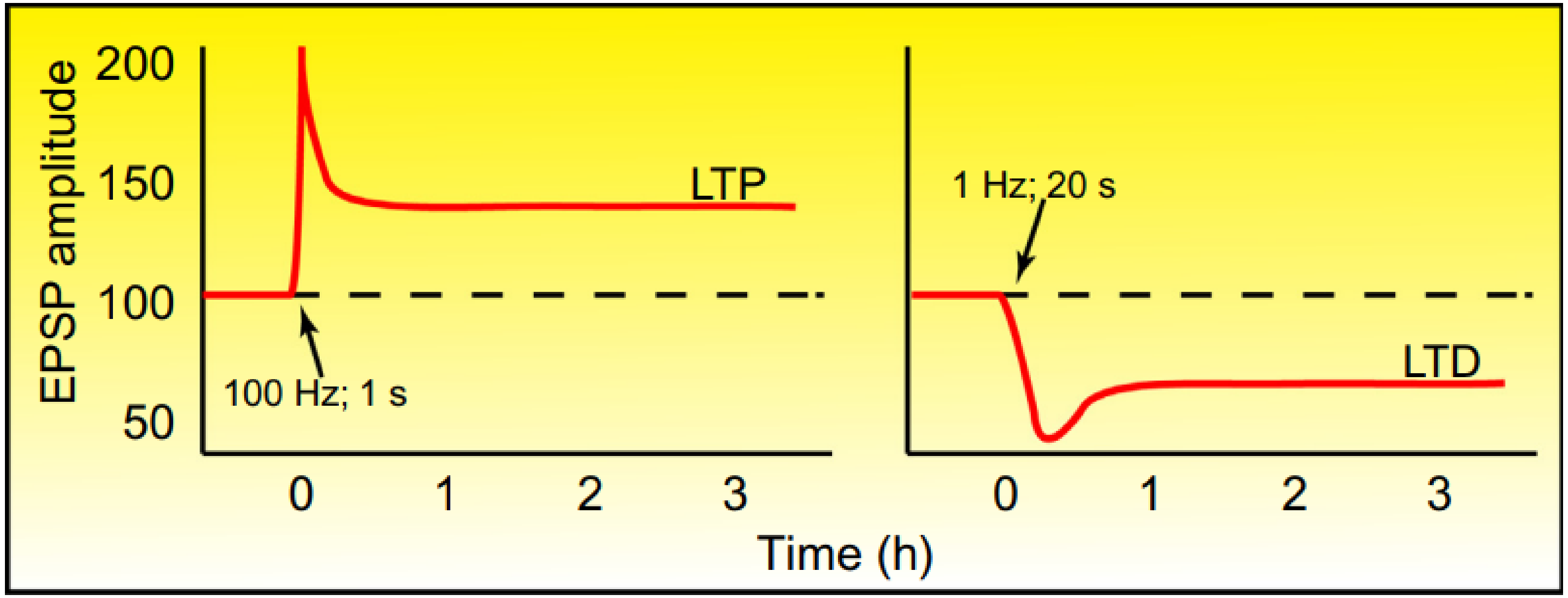


Figure: Long-term potentiation (LTP) and long-term depression (LTD).

Plots of excitatory postsynaptic potential amplitude at a hippocampal synapse over time during two different stimulus patterns. (Left panel) Following a long burst of high-frequency stimulation (100 Hz for 1 s), synapses strengthen, leading to a larger EPSP amplitude, and this is maintained for hours (LTP). The transient spike in strengthening that occurs immediately after the 100 Hz stimulus train results from post-tetanic potentiation. (Right panel) Following a low-frequency train of activity (1 Hz for 20 s), synapses weaken persistently, leading to a smaller EPSP amplitude (LTD).

Image from: *Meriney, Stephen D. (2019). Synaptic Transmission || Synaptic Plasticity. , (), 287–329.*

Synaptic plasticity: Adapting the connections

- **<u>Spike timing dependent plasticity (STDP):</u>**
  - The relative timing of input and output spikes determines the polarity of synaptic change.
- The timing between presynaptic and postsynaptic spikes
  - Can determine whether the change in synaptic strength is positive or negative
- ***Hebbian STDP***: If the presynaptic spike occurs slightly before the postsynaptic spike (e.g., 1–40 ms before), the synapse is strengthened, whereas if the presynaptic spike occurs slightly after (e.g., 1–40 ms after), the synaptic strength is decreased.

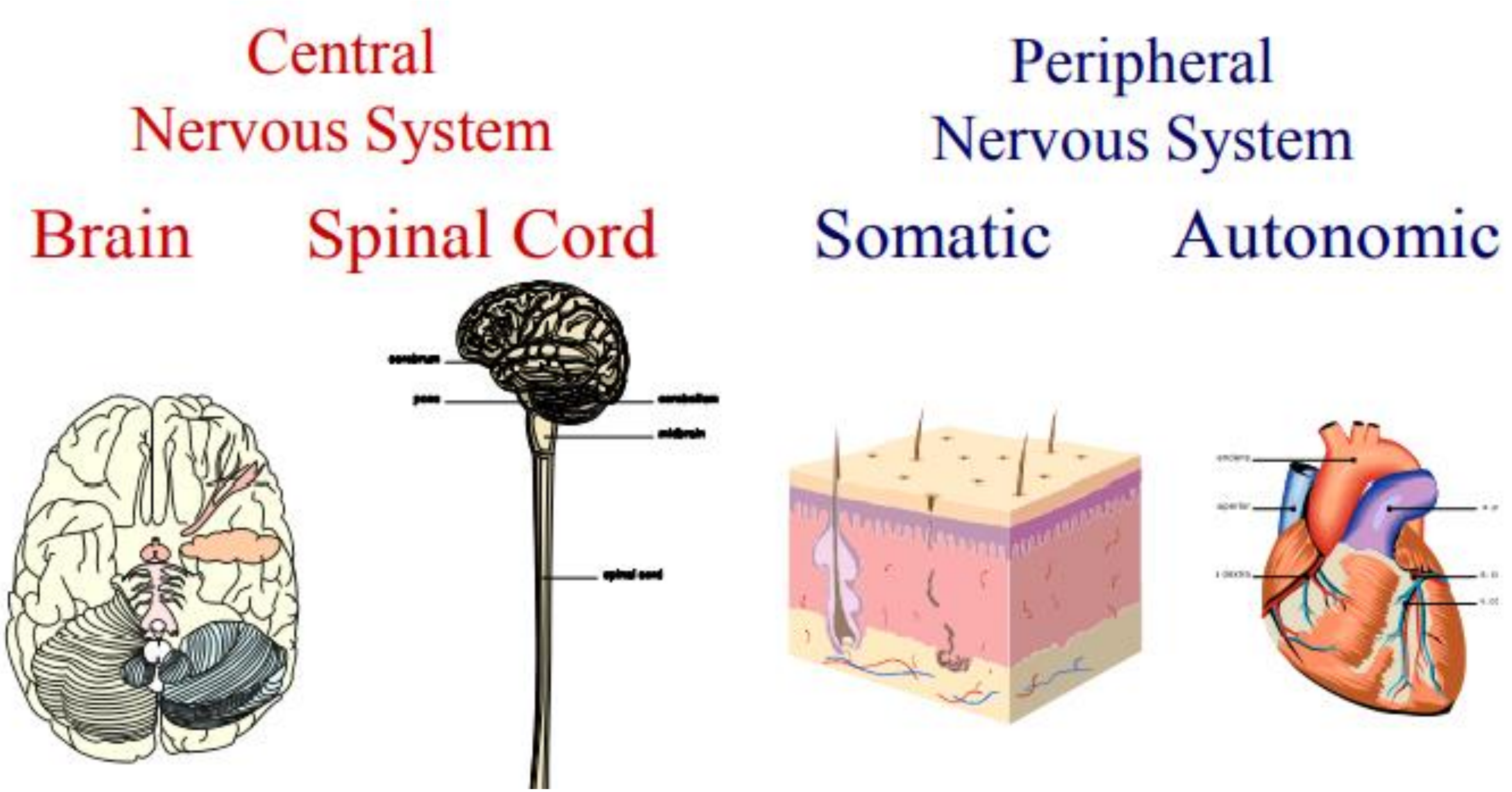
Synaptic plasticity: Adapting the connections

- Short-term facilitation/depression
  - The plasticity is rapid but not long-lasting.
- Short-term depression: The effect of each successive spike in an input spike train (sequence of spikes) is diminished compared to the preceding spike.
- Short-term facilitation: The effect of each successive spike has a larger effect than its predecessor, until a saturation point is reached

Brain Organization, Anatomy, and Function

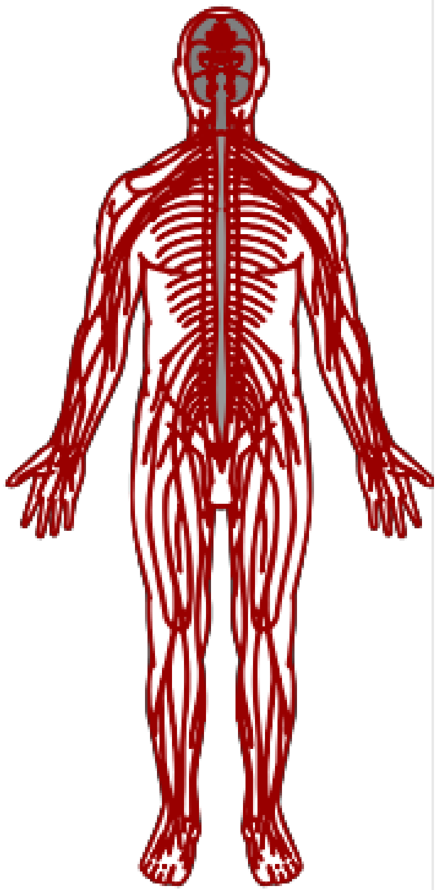
- The design of a brain-computer interface typically involves choices regarding which brain areas to record from and, in some cases, which brain areas to stimulate.
- The human nervous system can be broadly divided into
  - The central nervous system (CNS).
    - The CNS consists of the brain and the spinal cord.
  - The peripheral nervous system (PNS).
    - The PNS consists of the somatic nervous system (neurons connected to skeletal muscles, skin, and sense organs) and the autonomic nervous system (neurons that control visceral functions such as the pumping of the heart, breathing, etc.).

Brain Organization, Anatomy, and Function



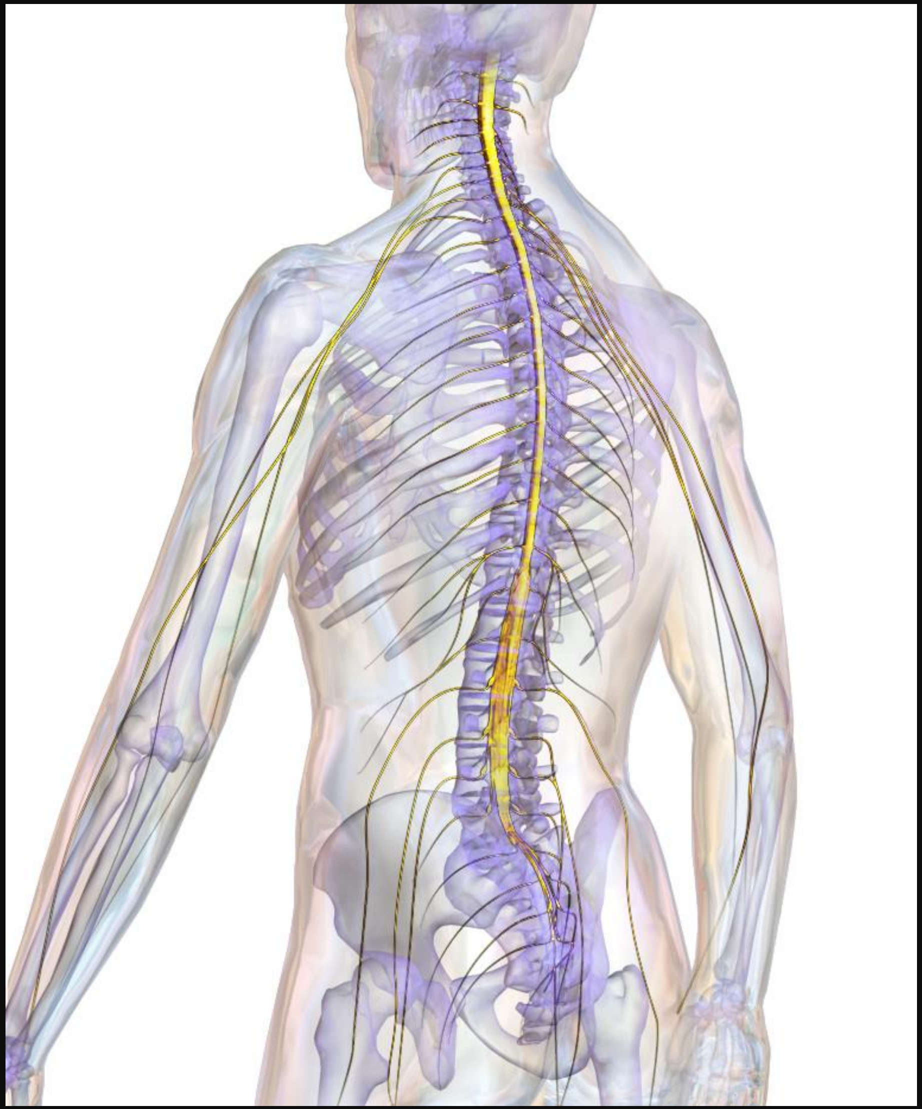
Skeletal/Somatic Nervous System

- Nerves that connect to voluntary skeletal muscles and to sensory receptors
- Afferent Nerve Fibers (incoming)
  - Axons that carry info away from the periphery to the CNS
- Efferent Nerve Fibers (outgoing)
  - Axons that carry info from the CNS outward to the periphery



Autonomic and Central Nervous System

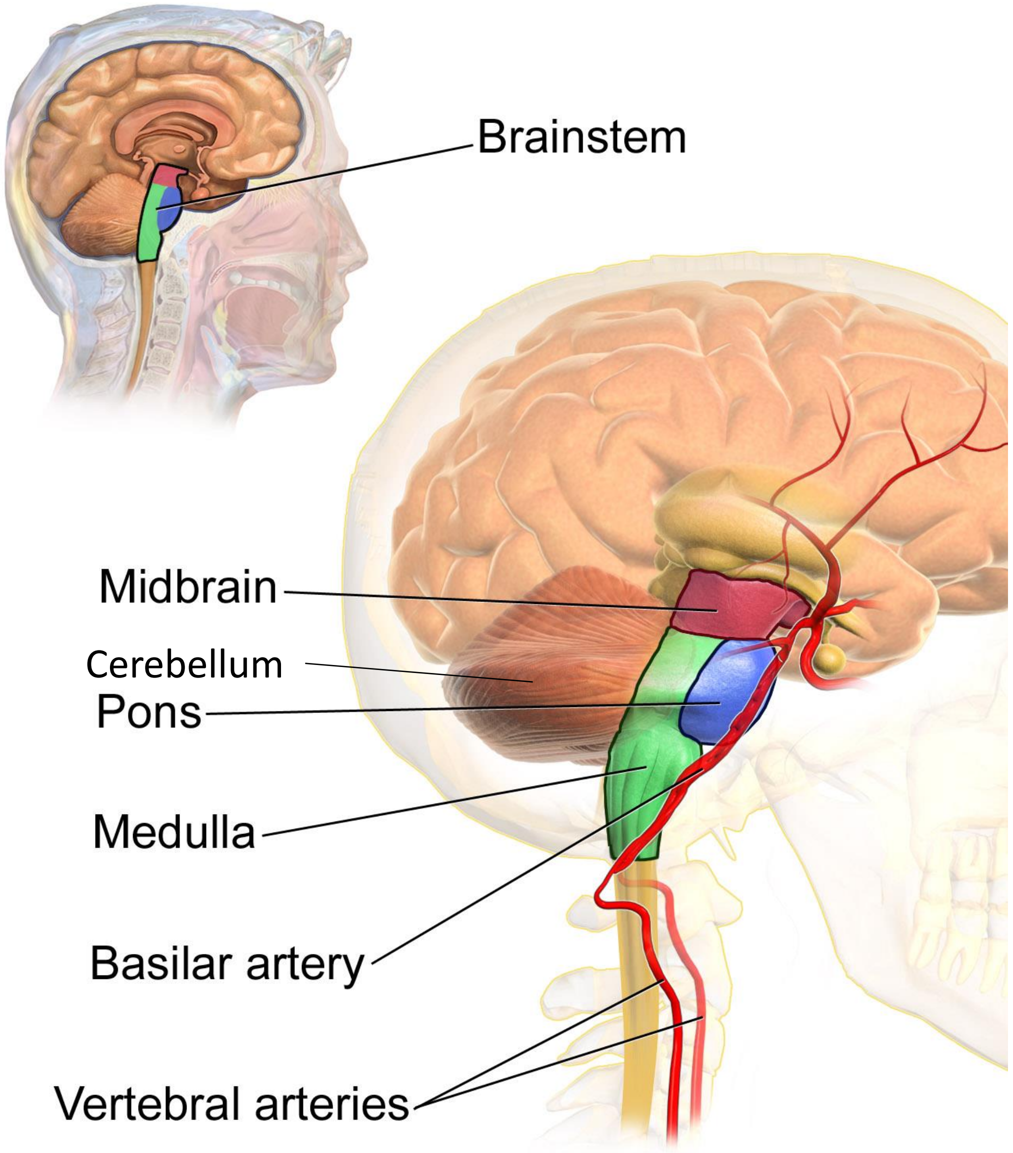
- Autonomic: Nerves that connect to the heart, blood vessels, smooth muscles, and glands
- CNS = Brain + Spinal Cord
- Spinal Cord
    - Local feedback loops control reflexes
    - Descending motor control signals from the brain activate spinal motor neurons
    - Ascending sensory axons transmit sensory feedback information from muscles and skin back to brain



This Photo by Unknown Author is licensed under CC BY

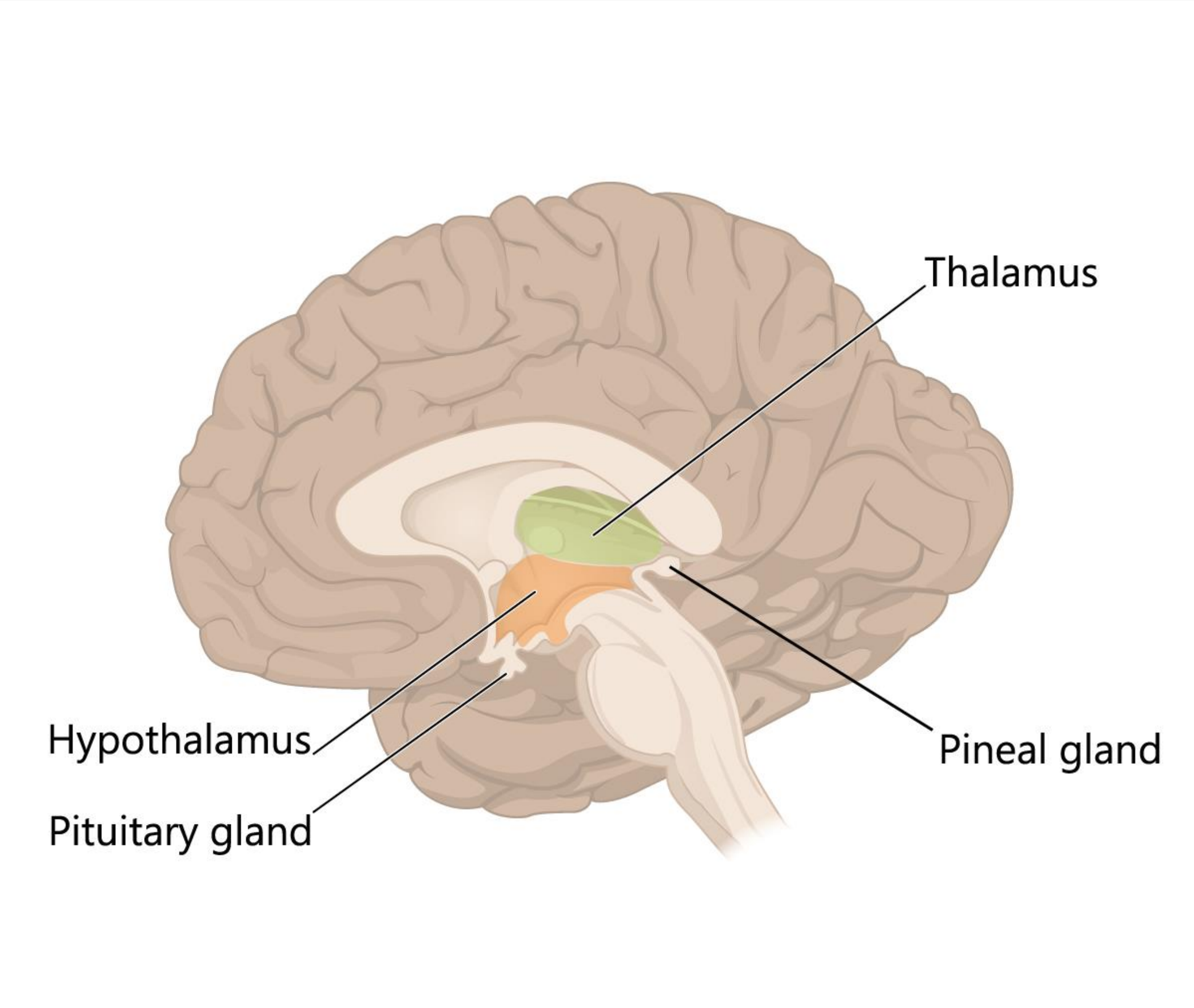
Major Brain Regions: Brain Stem

- Medulla: Breathing, muscle tone and blood pressure
- Pons: Connects brainstem with cerebellum & involved in sleep and arousal
- Cerebellum: Coordination of voluntary movements and sense of equilibrium
- Midbrain: Eye movements, visual and auditory reflexes



Major Brain Regions: Diencephalon

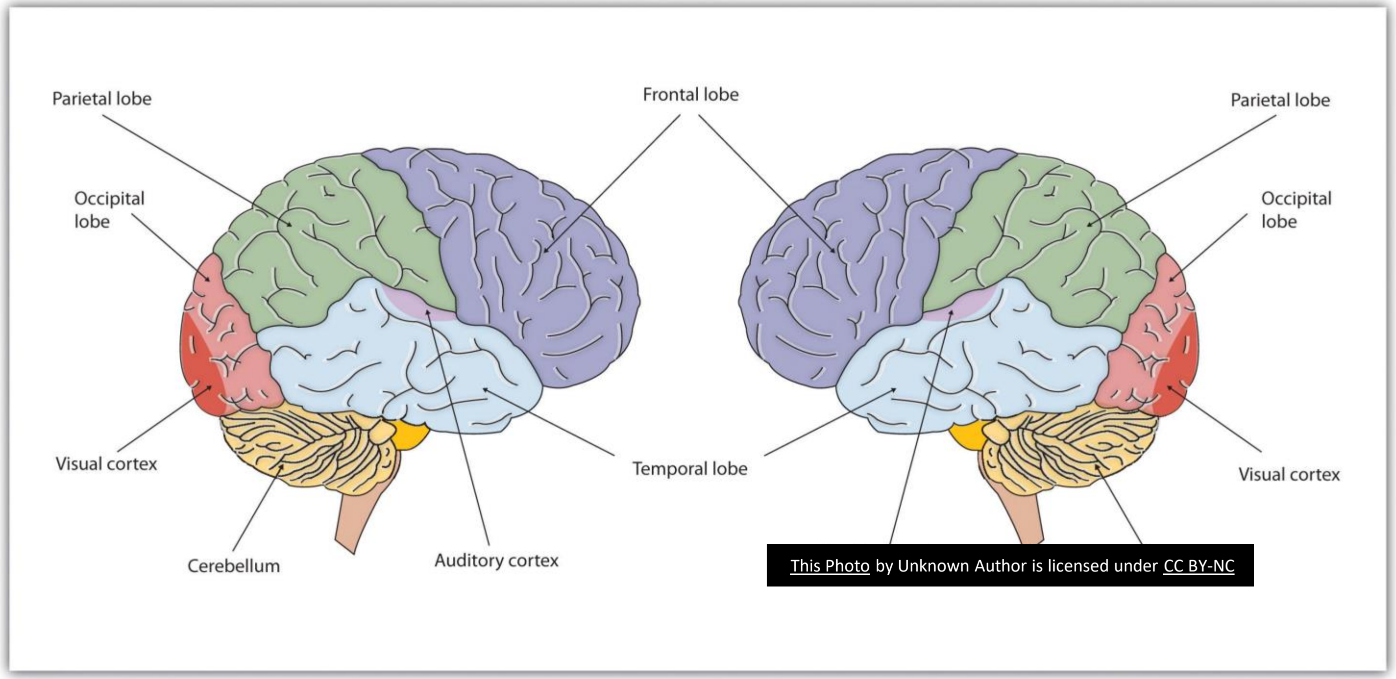
- Thalamus: Relay station for all sensory info (except smell) to the cortex
- Hypothalamus Regulates basic needs fighting, fleeing, feeding, and mating



This Photo by Unknown Author is licensed under CC BY-SA

Major Brain Regions: Cerebral Hemispheres

- Consists of Cerebral cortex, basal ganglia, hippocampus, and amygdala
- Involved in perception and motor control, cognitive functions, emotion, memory, and learning



This Photo by Unknown Author is licensed under CC BY-NC

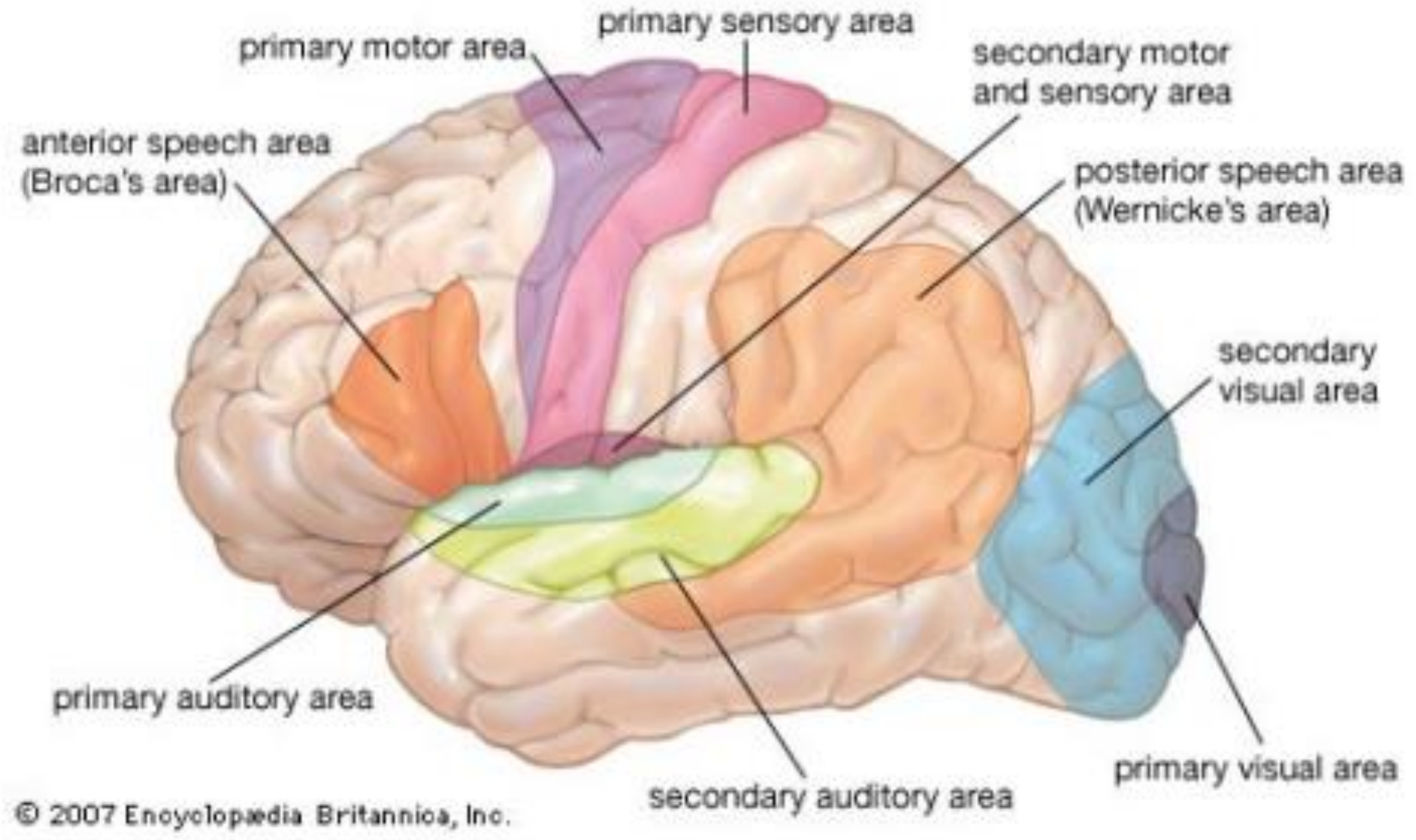


Figure 2.2: Regions of the cerebral cortex [Goldberg, 2002]

Cortical area	Function
Auditory association area	Complex processing of auditory information
Auditory cortex	Detection of sound quality (loudness, tone)
Broca's area (speech center)	Speech production and articulation
Prefrontal cortex	Problem solving, emotion, complex thought
Premotor cortex	Coordination of complex movement
Primary Motor cortex	Initiation of voluntary movement
Primary somatosensory cortex	Receives tactile information from the body
Sensory association area	Processing of multisensory information
Gustatory area	Processing of taste information
Wernicke's area	Language comprehension
Primary Visual Cortex	Complex processing of visual information